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This AASERT program augmented the original PRET program and supported work in three primary areas: (1) dynamics and control of rotating stall, (2) nonlinear control of rotating stall using novel actuation, and (3) modeling of thin film deposition for superconducting thin films. The goal of the first two activities was to develop new insights and actuation technolgies for rotating stall and surge, to overcome some of the limitations of traditional actuation techniques (bleed valves and air injection). The goal of the third activity, begun after the initial student supported by the grant left Caltech, was to develop modeling and control approaches for complex, physical systems, including control of microstructural properties of materials using macroscopic actuation.

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Robust Nonlinear Control of Stall and Flutter in Aeroengines

AASERT Grant

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FINAL REPORT
1 July 1997 to 30 June 2001

1 Background and Objectives

The parent grant for this AASERT proposal is a part of the AFOSR Partnerships for Research, Excellence and Transition (PRET) program was established in July 1995. The PRET program was a university based research program involving strong ties with industry to accelerate the transition of research results into industry. The project coordinator for the PRET program was Petar Kokotovic (UCSB) with co-PIs A. H. Epstein (MIT), E. M. Grietzer (MIT), A. J. Krener (UC Davis), R. M. Murray (Caltech), and J. D. Paduano (MIT). The industrial partner was the United Technologies Research Center.

The AFOSR-PRET Center assembled a team of researchers in nonlinear control theory (University of California and Caltech) and in compressor unsteady dynamics (MIT) to develop and test new techniques for robust nonlinear control of aeroengine instabilities, specifically compression system rotating stall and surge, and compressor blade flutter. The program coordinated the scientific base and proven approaches for dynamical analysis and control of rotating stall and surge developed at United Technologies Research Center (UTRC) and MIT with new robust nonlinear control design techniques developed at UC Santa Barbara, UC Davis, and Caltech.

This integrated effort had two primary goals: 1) to generalize and advance robust nonlinear control theory by applying it to real-world aeroengine instability issues, thus establishing a "fast-track" for transitioning relevant design techniques and software to industry, and 2) to generalize and apply proven nonlinear dynamics and control concepts used for rotating stall and surge control to an important new arena: active control of turbomachine aeromechanical instabilities (flutter). The outcomes included new and practicable avenues for improving reliability, operability, and performance of both military and civil gas turbine engines through use of robust nonlinear control.

This AASERT program augmented the original PRET program and supported work in three primary areas: (1) dynamics and control of rotating stall, (2) nonlinear control of rotating stall using novel actuation, and (3) modeling of thin film deposition for superconducting thin films. The goal of the first two activities was to develop new insights and actuation technologies for rotating stall and surge, to overcome some of the limitations of traditional actuation techniques (bleed valves and air injection). The goal of the third activity, begun after the initial student supported by the grant left Caltech, was to develop modeling and control approaches for complex, physical systems, including control of microstructural properties of materials using macroscopic actuation.

2 Accomplishments

Dynamics and control of stall

We investigated the behaviour of higher order Galerkin expansions of the Moore-Greitzer model of general transients in aeroengine compression systems. Assuming steady state entrainment of the higher Fourier modes of the rotating stall cell helped establish a framework for a simplified numerical analysis of the bifurcating solutions corresponding to rotating stall. For small values of the Greitzer surge parameter (B) we were able to describe general trends in the character of the pure stall solutions. The rotating stall characteristic was shown to exhibit deep hysteresis with a cubic compressor characteristic, establishing the fact that deep hysteresis to a certain extent is a multi-mode phenomena. Elimination of the hysteresis associated with the bifurcation into stall was accomplished in simulations with a combined feedback on the displacement from the peak of the compressor characteristic and the magnitude of the first mode amplitude of the stall cell. Behaviour for larger values of the B parameter was also investigated and novel surge/stall relaxation oscillations corresponding to classic surge are discovered.

This work was documented in a journal article that appeared in the *International Journal of Control.*

Novel Actuation

Two actuation schemes were investigated. The first involved a variable geometry hub, which was used to redirect the flow of air from the compressor from the hub region to the tip region. This was thought to be a viable approach to actuation based on a 1954 AMS Technologies patent that exploited hub versus tip blocakage effects. The second actuation technique was through the use of synthetic jets, an actuation technique which had recently been developed by Ari Glezer at Georgia Tech.

A prototype variable geometry hub was constructed and tested on the Caltech compressor rig. The hub used four solenoid valves to move small wedges that deflected flow from the hub region to the tip region. The valves were computer controlled and the phasing of the actuation could be linked to the phase of the rotating stall disturbance in the compressor. Although some effects of changing the hub geometry were observed, we were not able achieve effective closed loop control. A diagram of the device is shown in Figure 1. A second attempt at a variable geometry hub using fluid blockage (injected air) was considered by determined not to be viable.

A final approach was also initiated, using synthetic jets. The basic idea was to create a small cavity, driven by a speaker, with a slot through which air could enter and exit the cavity. At sufficiently high frequency and high amplitude oscillations of the speaker, a "synthetic jet" is produced by exploiting acoustic streaming. The student working on the project, Sean Humbert, spent a summer working at United Technologies Research Center (UTRC) and helped develop a simulation of a directed synthetic jet that was later used by UTRC in applications to rotorcraft. Unfortunately, the student working on the project left Caltech before construction of the actuation device for use at Caltech could be completed.

This work is documented in an internal presentation to the PRET team and also an internal UTRC technical report.

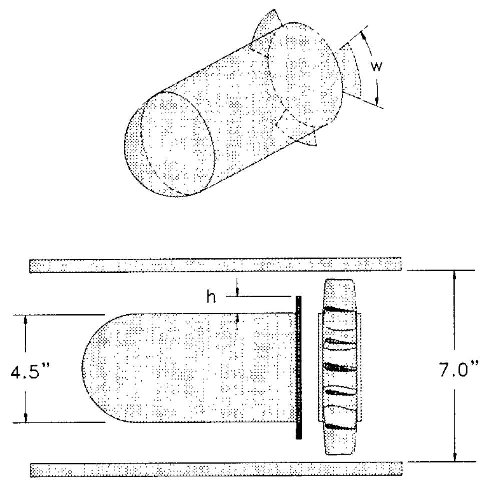

Figure 1: Variable geometry hub mechanism.

Modeling of Materials Processes

Based on some of the work in control of fluids systems initiated under the PRET program, the PI became interested in control of other continuous physical media using reduced order modeling and actuation. One area that seems to hold promise is the control of materials, both in fabrication and use. We concentrated on one specific material system, that of MOCVD fabrication of superconducting thin films, in conjunction with a DARPA program that was supporting experimental work in growth of YBCO.

For closed-loop control of thin film deposition, one would like to directly control film properties such as roughness, stress, or composition, rather than process parameters like temperatures and flow rates. This requires a model of the dynamic response of film properties to changes in process conditions. Direct atomistic simulation is far too slow to be used in this capacity, but a promising approach we have explored is to derive reduced-order dynamic models from atomistic simulations. We considered film growth on a vicinal surface using a kinetic Monte Carlo model. The temperature range spanned the transition from smooth step flow to rough island growth. Proper Orthogonal Decomposition was used to extract the dominant spatial modes from the KMC simulations. Only five spatial modes were needed to adequately represent the roughness dynamics for all simulated times and temperatures, indicating that a 5-state model may be sufficient for real-time roughness control.

These results have subsequently led (under other funding) to new results in the use of unsteady processing conditions to achieve film properties that cannot be achieved with steady conditions. This is one of the elements of a new MURI at Caltech, sponsored by ARO and which the PI and AASERT student (Martha Gallivan) are active members.

3 Personnel Supported

J. Sean Humbert (graduate student, 1996-1998)
Martha A. Gallivan (graduate student, 1999–2000)

4 Publications

1. J. S. Humbert and A. J. Krener, "Dynamics and control of entrained solutions in multi-mode Moore-Greitzer compressor models," *International Journal of Control*, 71:(5) 807-821, 1998.

2. M. A. Gallivan, R. M. Murray, and D. G. Goodwin, "The Dynamics of Thin Film Growth: A Modeling Study," Electrochemical Society, May 2000.

3. M. A. Gallivan, R. M. Murray, and D. G. Goodwin, "Kinetic Monte Carlo Simulation of Dynamic Phenomena in Thin Film Growth," 2000 Materials Research Society Spring Meeting.